RURAL DEVELOPMENT
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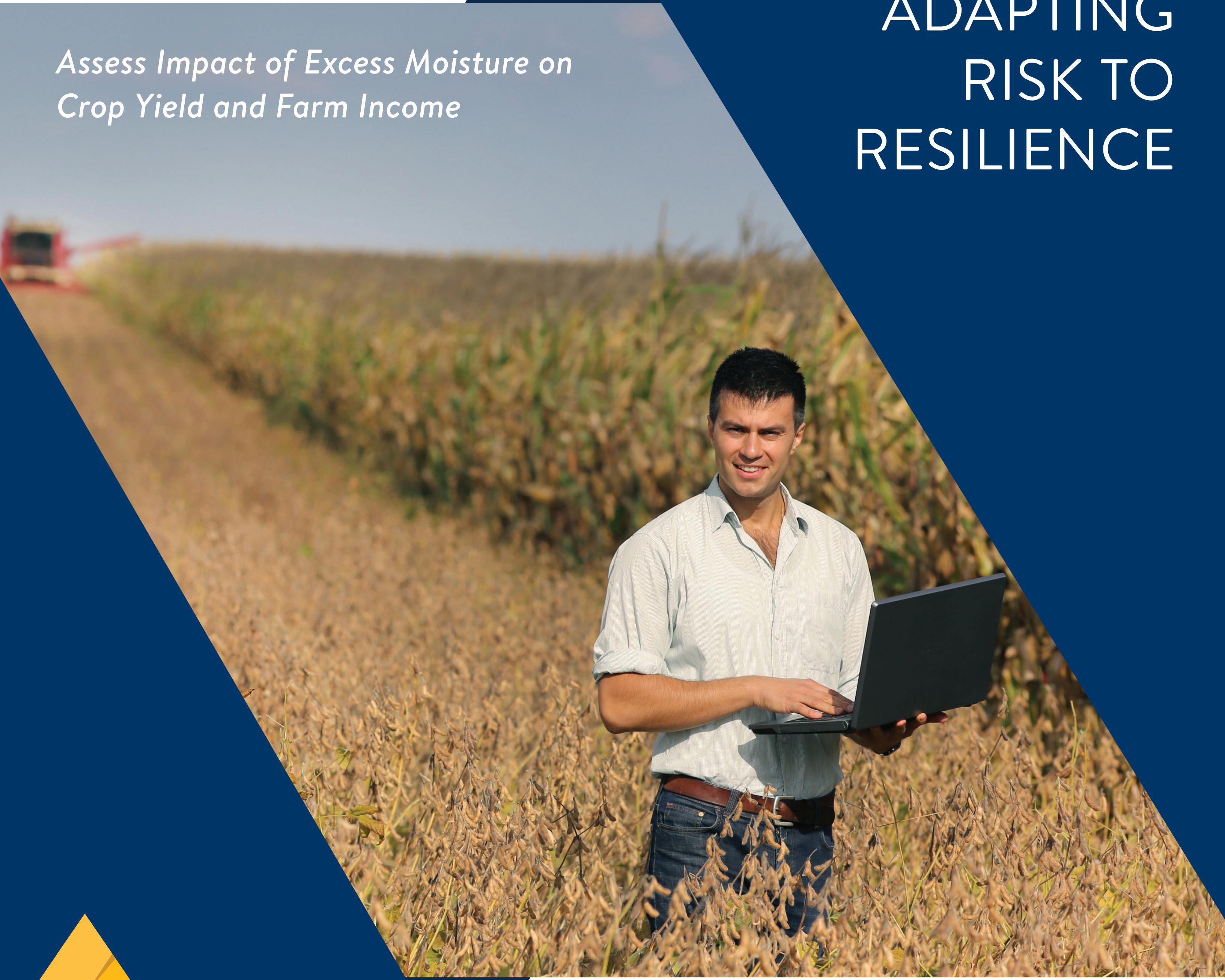
PHASE 1

ADAPTING RISK TO RESILIENCE

Assess Impact of Excess Moisture on Crop Yield and Farm Income



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BRANDON UNIVERSITY

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Rural Development Institute

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Foreword

Manitoba's rapidly changing climate conditions are characterized by increased frequency and intensity of extreme moisture events. For instance, four of the top ten Assiniboine River floods and five of the top ten Red River floods took place during the last 25 years. In addition to these spring floods, other extreme moisture events include prolonged or intense periods of rain. Generally, from an ag-producer's perspective, these events result in soil moisture in extreme of field capacity for a period sufficient to significantly inhibit crop production.

Moreover, the impacts of such events can be local or regional as well as downstream. For producers, the impacts may be short-term, prolonged or persistent depending on the locale, previous moisture mitigation strategies, and the local and regional water infrastructure. These extreme water events harm farm livelihoods as well as the well-being of all downstream rural municipalities and urban centres having to deal with the social, economic and environmental costs due transportation interruptions, property damage, and agricultural run-off impacts on surface and ground water quality.

There are several longer term strategies producers can invest in to manage extreme moisture in their fields. Reducing the risk of crop loss or reductions in yield and quality are generally the main reasons why producers make such investments. Others at the local and regional levels may also benefit from these water management practices as well (e.g., reduced peak flows). This project aims to provide agricultural producers at the early stage of long-term planning with critical factors in estimating socio-economic costs and benefits of different on-farm extreme moisture practices, along with identifying other stakeholder considerations.

To achieve that goal, this project consists of three main activities and took place in two distinct phases. The focus of Activity 1 was to provide producers with an on-farm costs and benefits framework to help evaluate different investment strategies for managing extreme moisture. Activity 2 focused on using farm models to provide information on the impact on yield and farm income due to extreme moisture. Lastly, Activity 3 focused on identifying the downstream impacts and costs of extreme moisture events with a particular focus on the 2011 Assiniboine River flood. For each activity, Phase 1 consisted of gathering and synthesizing academic and other publicly available information and data. Phase 2 of the project sought to get feedback from producers and other stakeholders in an effort to validate the findings of the Phase 1 activities. Overall, the 2 phases of the 3 activities of this project resulted in the completion of 6 reports which are outlined in Figure 1.

Summary of the 6 reports indicating the main objectives for each phase and activity

	ACTIVITY 1	ACTIVITY 2	ACTIVITY 3
	Economic Costs and Benefits Analysis of Excess Moisture Investments	**Impacts of Excess Moisture on Crop Field and Farm Income**	**Downstream Effects of Excess Moisture in Manitoba**
PHASE 1	1. Identify farm investment options for excess moisture management. 2. Identify of on- and off-farm costs and benefits of investment options. 3. Quality costs and benefits of investment options and select suitable proxies for qualitative costs and benefits. 4. Develop a framework to assess costs and benefits of excess moisture investment options.	1. Identify, calibrate and adapt a farm model that could be simulating the impact of excess moisture events in southern Manitoba's field conditions.	1. Identify the physical and socio-economic impacts of excess moisture 2. Identify the direct the indirect costs excess moisture losses. 3. Identify the downstream economic impacts of excess moisture.
PHASE 2	1. Validate the economic cost-benefit framework of proposed investment options of farm-level extreme moisture management. 2. Determine what extreme moisture management strategies are currently being use. 3. Evaluate the willingness of producers to adapt their farm using proposed extreme moisture management strategies. 4. Conduct a Manitoba local market survey to validate cost estimations used in the development of cost-benefit framework.	1. Identify current yield forecasting tools available and being used by stakeholders at different scales of operations. 2. Evaluate the willingness of producers and other stakeholders in crop yield forecasting models.	1. Validate the completeness and accuracy of the physical and socio-economic impacts of excess moisture. 2. Assess the relevance and usefulness of the information for the procedures and stakeholders. 3. Identify other effects, outcomes, and strategies that producers and stakeholders considered in response to the 2011 Assiniboine River Flood

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Executive Summary

Climate change, through its influence on the ecosystems, affects all components of humans' livelihood and food security with major impacts on rural areas. Rural communities experience these impacts very directly as most ecosystems have a rural dimension. Natural risks especially natural drought and flood occurrences caused by weather extremes constantly threaten the agriculture economy. Manitoba's rapidly changing climate conditions are characterized by increased frequency and intensity of excess moisture events. Prolonged excess moisture conditions cause negative effects on agricultural operations that result in loss of crop yield, quality, and farm income. It is necessary for Manitoba producers to use yield forecast tools in order to understand the scope of excess moisture events influencing crop yield, and quality. This information would allow producers to respond appropriately in order to overcome the disaster. Moreover, crop yield forecasts are important for determining the difference between potential and actual yields aiding government and producer organizations for development of export-import policies, food security policies, and efficient land management practices.

Traditional crop yield estimates, conducted through farm surveys or by experts based on their evaluation of crop conditions, are somewhat subjective, time-consuming and often unrepresentative due to small sample sizes. Farm simulation models use climate state analysis to forecast crop yields and offer several benefits over traditional methods, including precision, reduced costs and the elimination of human-related biases and errors. The state of the climate can be analysed by using various statistical methods such as frequency, magnitude, and trend analysis. These analyses are employed in a simulation model to predict future changes in climatic conditions and its subsequent affect on crop yield. Simulated farm models assess crop yield gaps (quantified as the difference between potential and actual farm yields), impact of climate change on future crop yields, and land-use change. Several farm models are available to measure the effects of weather extremes, and excess moisture on crop yields. However, these models are calibrated in different climatic zones with region specific crop characteristics. Assessment of impacts and adaptability to climate change at Manitoba's local scale necessitates parameterization of models to incorporate Manitoba's local conditions and management practices.

To analyze the potential impacts of projected climate scenarios on crop yield variability in the southern Manitoba, RDI has calibrated a farm model called "AquaCrop" using Manitoba's 30-year historical climatic data (1990 – 2019) and simulated local crop characteristics in the model interface. This farm model has the ability to simulate excess moisture management scenarios and can be of use to many – producers, farm production consultants, planners, and economists to make business informed decisions in their areas of expertise at the targeted scale. The overall aim of this project is to assist Manitoba producers in better understanding of on-farm investments to manage excess moisture and to catalogue downstream impacts of such events. The analysis will take place in multiple phases. Three activities frame phase-1 of this project:

Activity – 1: A selection of 3-5 investment strategies to manage on-farm excess moisture

Activity – 2: Adaptation of a farm model to assess the impact of excess moisture on crop yield and farm income

Activity – 3: Identification of downstream costs and benefits of excess moisture event

The aim of this report is to focus the objectives of Activity – 2 by developing a pro-active and fiscally responsible approach to mitigating the effects of excess moisture in Manitoba's metrological conditions. The ultimate goal of developing this risk management approach is that Manitoba's agricultural producers have access to, and are able to use a farm model to manage risk associated with excess moisture, and are therefore more prepared and less vulnerable to farm flooding situations.

Activity 2

Adaptation of a Farm Model to Assess the Impact of Excess Moisture on Crop Yield and Farm Income

Objectives:

① Identify, calibrate, and adapt a farm model that could be simulating the impact of excess moisture events in Southern Manitoba's field conditions (Phase – 1).

② Run the model to simulate a baseline scenario for a typical farm case study in Southern Manitoba (Phase – 2).

③ Analyze model's efficiency statistically to validate model's parameters (Phase – 2).

Beginning at the Beginning with Defining Excess Moisture

In an agricultural setting, a significant amount of soil moisture that is sufficient to cause negative effects on agricultural operations, including excessive soil erosion, equipment trafficability, loss of seed, reduced crop yield/quality, and subsequently loss of farm income is regarded as excess moisture. Prolonged rainfall, spring snowmelt, and flooding from rivers/dams overflowing are biggest causes of excess moisture in the soil, and leave crops oversaturated.

Background

Climate change, through its influence on the ecosystems, affects all components of humans' livelihood and food security with major impacts on rural areas. Rural communities experience these impacts very directly as most ecosystems have a rural dimension. Agriculture is among the most vulnerable sectors to climate change due to its dependency on weather conditions. Natural risks especially natural drought and flood occurrences caused by weather extremes constantly threaten the agriculture economy. Continued growth in the global population puts greater pressure on the agriculture sector to produce enough food to feed the world population. However, rapidly changing climate conditions are becoming a challenge to meet growing food demands as extreme weather conditions resulting from climate change effects create challenging decision-making situations for the agriculture industry. Climate change is likely to contribute substantially to food insecurity in the future, by increasing food prices, and reducing food production.

In Canada, excess soil moisture has been identified as a main issue for crops in western regions. Excess moisture in the Prairies has occurred as a result of major rainfall events in summer and fall and also high volumes of snowmelt runoff in spring. Manitoba's rapidly changing climate conditions are characterized by increased frequency and intensity of excess moisture events. Over the 1966 – 2005 period, 72 % of postharvest claims for crop losses by farmers in Manitoba and Saskatchewan were caused by excess moisture (37 %) and drought (35 %). However, in recent years (2005 – 2016) in Manitoba and Saskatchewan, the crop loss claims due to excess moisture significantly increased (52 %) (MASC, 2017; SCIC, 2017). Manitoba has a long history of flooding, including major floods in 1950, 1997 and 2009, and the most recent flood of 2011 was of a scope and severity never before experienced in the province. Four of the top ten Assiniboine River floods and five of the top ten Red River floods took place during the last twenty-five years. The greatest impact on these floods is the mean rainfall that occurs in May to June, which has increased significantly since 1960, but mostly after the mid-1990s (Szeto et al., 2015). Climate models show that Canada's agricultural regions will likely see drier summers from coast to coast, but increased winter and spring precipitation. This means that farmers may have to deal with both too much water during the seeding season and too little water during the growing season, all in the same year (Climate Atlas of Canada, 2019).

Problem Statement

Flood and drought have increased in frequency and intensity around the world over the past 50 years and weather simulation models predict a 30 % increase in excess moisture events by 2030 (Rosenzweig et al., 2002). In Manitoba, main drivers of excess moisture conditions are intensive rainfall, and spring snow melt which result in flooding conditions at arable lands. The Assiniboine River Basin in the southeastern Canadian Prairies is one of the most flood-prone regions in Canada. Manitoba's Flood Review Task Force Report has summarized the severity of the 2011's flood experienced in the province (Government of Manitoba, 2013). Three million acres of cultivated farmland went unseeded in 2011. Thousands of cattle had to be relocated. More than 650 provincial and municipal roads and nearly 600 bridges were damaged, disrupting transportation networks throughout the province.

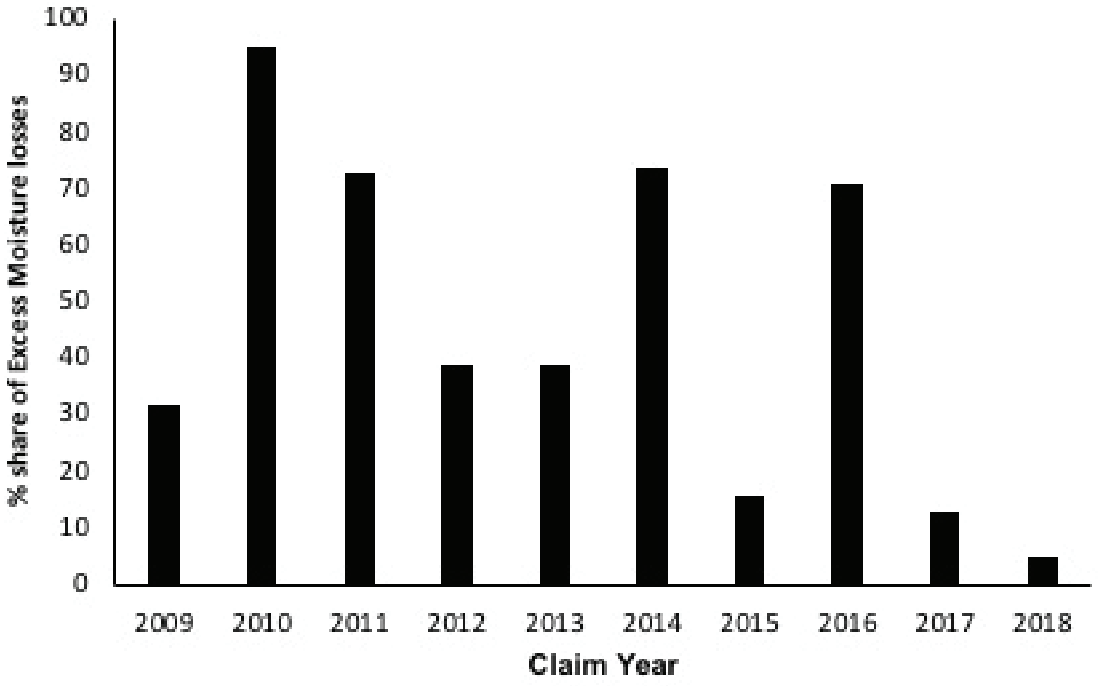
It is necessary for Manitoba producers to use yield forecast tools in order to understand the scope of excess moisture events influencing crop yield, and quality. This information would allow producers to respond appropriately in order to overcome the disaster. Moreover, crop yield forecasts are of great significance for farm production consultants, planners, and economists to make business informed decisions in their areas of expertise at the targeted scale. Traditional crop yield estimates, conducted through farm surveys or by experts based on their evaluation of crop conditions, are somewhat subjective, time-consuming and often unrepresentative due to small sample sizes (Basso et al., 2013). Farm simulation models use climate state analysis to forecast crop yields. These analyses are employed in a simulation model to predict future changes in climatic conditions and its subsequent affect on crop yield. Several farm models are available to measure the effects of weather extremes, and excess moisture on crop yields. However, these models are calibrated in different climatic zones and with different regional crop characteristics. Assessment of impacts and adaptability to climate change at Manitoba's local scale necessitate parameterization of models to incorporate Manitoba's local conditions and management practices.

The aim of this report is to develop a pro-active and fiscally responsible approach to mitigating the effects of excess moisture in Manitoba's metrological conditions. The ultimate goal of developing this risk management approach is that Manitoba's agricultural producers have access to, and are able to use a farm model calibrated in Manitoba's metrological conditions to manage risk associated with excess moisture, and are therefore more prepared and less vulnerable to farm flooding situations.

The Anatomy of Yield Forecasting

Water in the form of soil moisture; is an essential resource for farmers growing any crop. An adequate amount of soil moisture is required to facilitate transporting important soil nutrients through the plant and keeping the plant from dehydrating. Without required amount of soil moisture, plant development and survivability is affected. However, excessive amounts of soil moisture can also have negative effects on agricultural efforts; including reduced crop yield/quality, equipment trafficability, soil erosion, loss of seed, and damaging infrastructure and property. Excess moisture conditions can result from prolonged rainfall, flooding from rivers/dams overflowing, and flow caused by spring snowmelt. Farmers in Manitoba frequently face the challenge of excess moisture in the soil profile during the springtime, which could lead to delays in planting and potential yield loss. The Excess Moisture Insurance Program (EMIP) covers all farmers in Manitoba with a crop insurance contract with Manitoba Agricultural Services Corporation (MASC). MASC paid a total of $119 million claims in 2011 to affected producers under the EMIP, because of the inability of the producers to seed due to excess soil moisture conditions (MASC, 2012). The severity of excess moisture events, and their subsequent impact on crop yield is not uniform every year. Figure 1 shows the percent share of excess moisture losses in total losses for all crops in a year (MASC, 2019). Variability in the losses caused by excess moisture conditions every year highlights the importance of accurate, and precise yield forecasting in order to make business informed decisions.

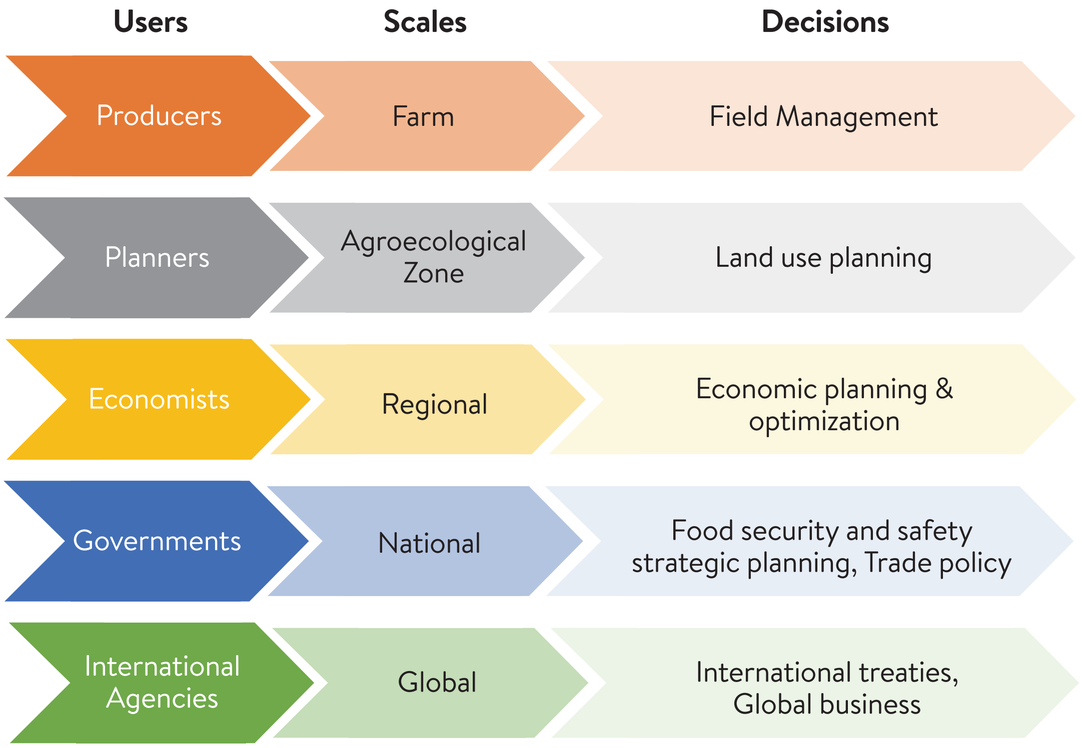
Figure 1: Percent share of excess moisture losses in total losses for all crops in a year



Crop yield estimation allows producers to quantify the impact of climate change on future crop yields by menstruating the difference between potential and actual farm yields, and help in appropriate mitigation decision making without compromising smallholder livelihoods and rural development (Rosenstock et al., 2013). Various methods have been developed for quantifying crop at research plot level and also using simulation models at regional and national level. Traditionally, crop yield is estimated by farmer's earlier experience with the crop. Agricultural production is significantly affected by environmental factors. Weather influences crop growth and development, causing large intra-seasonal yield variability. In addition, spatial variability of soil properties, interacting with the weather, cause spatial yield variability. Yield forecasting models take these climate state analysis into account in order to forecast crop yields and offer several benefits over traditional methods, including precision, reduced costs and the elimination of human-related biases and errors.

Crop yield forecasts are important for determining potential and actual yield losses aiding government and producer organizations for development of export-import policies, food security policies, and efficient land management practices. Crop yield forecasts develop an understanding of precise impact of long term metrological variations on crop yield, allow managing risk associated with moisture extremes (excess or deficit), and cause reduction in the risks related with local or national food systems. Risk reduction contributes to improved outcomes in terms of the environment (better flows of and access to natural capital), socioeconomic aspects (increased farm income, employment, and economic growth), and health and nutrition (reduced diseases, morbidity, and mortality rates). Figure 2 summarizes that nature of decisions made with the help of yield forecasts by different categories of model users at their targeted scale.

Figure 2: Synergies of yield forecast models at different scales



Users	Scales	Decisions
Producers	Farm	Field Management
Planners	Agroecological Zone	Land use planning
Economists	Regional	Economic planning & optimization
Governments	National	Food security and safety strategic planning, Trade policy
International Agencies	Global	International treaties, Global business

The complexity of crop responses to soil moisture led to the use of empirical production functions as the most practical option to assess crop yield response to moisture extremes (excess/stress). The soil water balance is important for understanding the inputs and outputs of soil water. Following soil water equation developed by McGowan and Williams (1980) describes inputs and outputs of soil water.

$$\Delta S = (P + I) - (ET + U)$$

Where,

ΔS = Change in soil water storage

P = Water input by precipitation

I = Water input by irrigation

ET = Water output by evapotranspiration from the crop (transpiration) and soil (evaporation)

U = Drainage and seepage from the soil

If the change in water storage is higher than the upper threshold limit of crop water requirement, this field condition is regarded as excess moisture condition.

The interactions and complex feedback loops inherent in combining ecological and economic systems required a complex nonlinear system dynamics approach, which embraced the links between these systems (Low et al., 1999). In an agricultural setting, a system dynamics model allows the simulation of an actual in-field scenario to assess the impact of a treatment on different crop parameters e.g. yield, quality, plant survivability, and water productivity etc. Wide variations in soil, crop and climatic factors in different parts of the world, make the assessment of excess moisture conditions impacts on crop yield more complex. It is too costly and time consuming to conduct field experiments to evaluate the long-term impacts of excess moisture conditions for different combinations of factors. Therefore, as an alternative, computer models can be used to simulate the soil water balance under widely varying conditions to quantify the yield decline caused by excess moisture conditions. Once a model is calibrated and validated, it can be used as a good tool for assessing the impact of excess moisture conditions on crop yield in the local conditions.

Farm Models

Models represent systems that exist in real time on the farm (Loomis et al., 1979). Farm models are a useful tool to predict the growth, development and yield of a crop in response to the surrounding environment (Steduto et al., 2009). A model simplifies key components of factors influencing the growth of a plant including climate, crops types, soils, and management practices. Model simulations typically go through a calibration phase, where a model is adapted for a specific region or condition under the consideration of historically observed data. Several farm models are used around the world to predict different aspects of agricultural systems.

Scientific advancement and continuous data collection of weather parameters has enabled a better understanding of the earth's variable climate and the responses to human and natural influences (Moss et al., 2010). Predicting future yields are significantly dependent on the coupling of meteorological information and farm models. Detailed climate data are required to calibrate a farm model because frequently variable climatic features can greatly influence crop yields. The state of the climate can be analysed by using various statistical methods such as frequency, magnitude, and trend analysis (IPCC, 2013) to predict future changes in climatic conditions and its subsequent affect on crop yield. Assessment of impacts and adaptability to climate change at Manitoba's local scale necessitate parameterization of models to incorporate Manitoba's local conditions and management practices. Several crop simulation models exist, and the 10 more popular ones are noted in Table 1.

Table 1: Crop simulation models and their areas of focus

Model	Model Description
Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003)	DSSAT simulates growth, development and yield as a function of the soil-plant-atmosphere dynamics.
Cropping Systems Simulation Model (CropSyst) (Stockle et al., 2003)	CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and erosion.
Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003)	APSIM simulates water balance, N and P transformations, soil pH, and erosion.
Hybrid Maize Model (Hybrid-Maize) (Yang et al., 2004)	Hybrid-Maize simulates the growth of a corn crop under non-limiting or water-limited (rainfed or irrigated) conditions based on daily weather data.
Farm System Simulator (FSSIM) (Louhichi et al., 2010)	FSSIM assess at the farm level the impact of agricultural and environmental policies on performance of farms and on sustainable development indicators.

Model	Model Description
World Food Studies (WOFOST) (Diepen et al., 1989)	WOFOST simulates crop growth on the basis of photosynthesis, respiration and how these processes are influenced by environmental conditions.
Environmental Policy Integrated Climate Model (EPIC) (Williams et al., 1984)	EPIC simulates management decisions on soil, water, nutrient and pesticide movements, and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management.
Agricultural Policy Environmental Extender (APEX) (Williams et al., 1995)	APEX simulates the impact of land management strategies such as irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage.
Simulateur Multidisciplinaire pour les Cultures Standard (STICS) (Whistler et al., 1986)	STICS simulates agricultural production and nitrate leaching on the basis of soil heterogeneity.
Farm Design (FarmDESIGN) (Groot et al., 2012)	FFarmDESIGN evaluates the productive, economic and environmental farm performance.

A common feature of the majority of these models is the requirement for highly detailed input data and information about crop growth that are not available in most locations worldwide. To address these limitations, Land and Water Division of FAO (Food and Agriculture Organization of the United Nations), developed AquaCrop farm model in 2009 (Steduto et al., 2009; Raes et al., 2009). It requires a relatively small number of explicit and mostly intuitive parameters to be defined compared to other crop models, and has been validated and applied successfully for multiple crop types across a wide range of environmental and agronomic settings (Vanuytrecht et al., 2014).

AquaCrop Model

AquaCrop simulates yield response to soil moisture, and is particularly suited to assess the impact of soil moisture extremes on crop yield. The model was developed for the purpose of using relatively small number of explicit parameters in a balance of simplicity, accuracy, and robustness. The calculation procedure is grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system. Studies have shown that the AquaCrop model provided reasonable results for simulating crop yields in a wide range of geographical locations around the world (Araya et al., 2010; Andarzian et al., 2011; Karunaratne et al., 2011; Salemi et al., 2011; Stricevic et al., 2011; Vanuytrecht et al., 2011; Zinyengere et al., 2011; Abedinpour et al., 2012; Abrha et al., 2012; Mkhabela and Bullock, 2012; Iqbal et al., 2014).

The AquaCrop model has high precision in comparison with competing models; it has accurately predicted canopy cover, biomass, yield, soil water content, water use efficiency, and water production for wheat (Mkhabela et al., 2012; Iqbal et al., 2014), corn (Stricevic et al., 2011; Mhizha et al., 2014), sunflower (Stricevic et al., 2011), and potato (Casa et al., 2013; Rankine et al., 2014). Mkhabela and Bullock (2012) used AquaCrop to simulate wheat yield and soil water content on the Canadian Prairies (Saskatchewan and Manitoba) from experimental sites from 2003 through 2006. These studies clear point out AquaCrop is a valuable tool for simulating both wheat grain yield and soil water content in the Canadian Prairies.

Particular features that distinguishes AquaCrop from other crop models are:

- its focus on soil moisture;
- the use of canopy cover instead of leaf area index;
- the use of water productivity values normalized for atmospheric evaporative demand and CO2 concentration that confer the model an extended extrapolation capacity to diverse locations, seasons, and climate, including future climate scenarios;
- the relatively low number of parameters;
- input data which requires only explicit and mostly intuitive parameters and variables;
- a user-friendly interface;
- its considerable balance between accuracy, simplicity, and robustness;
- its applicability to be used in diverse agricultural systems that exists world wide;
- It allows easy verification of simulation results with simple field observations.

In AquaCrop, five crop development stages are: emergence, start of flowering, maximum rooting depth, start of senescence and physiological maturity (Steduto et al., 2009). These stages vary among different crop varieties and require calibration to accurately simulate localized yields. AquaCrop is designed to simulate the growth, biomass production, and harvestable yield of herbaceous crop types. It is important to note that this model is not intended currently to simulate perennial tree crops or vines (Steduto et al., 2012), for which yield

AquaCrop Operation

The AquaCrop model was chosen in part due to its relatively easy operation, open access software program availability, and providing user-friendly interfaces which do not require extensive modeling knowledge. The software also provides an interface to communicate visually how the various components of the modeling system are interacting. This offers a better method of communicating the complexity of the modeling system to the end user than conventional code based models. The AquaCrop model uses the water equation developed by Doorenbos and Kassam (1979) as a starting point for the model to determine the impact of excess moisture regimes at crop production. This equation has been widely used to estimate yield response to water by planners, economists and engineers (Howell et al., 1990).

$$\frac{(Y_x - Y_a)}{Y_x} = K_y \left(\frac{(ET_x - ET_a)}{ET_x}\right)$$

Where,

Yx = Maximum yield

Ya = Actual yield

ETx = Maximum evapotranspiration

ETa = Actual evapotranspiration

Ky = Proportionality factor between relative yield loss and relative reduction in evapotranspiration

Next two sections describe about the calculation scheme, and data in-put requirements of AquaCrop model.

Calculation Scheme of AquaCrop:

AquaCrop requires fewer parameters and inputs to simulate yield compared to other crop models, but still there is need to manually set up local parameters. Because above ground biomass and yield are determined by the available moisture in the soil, the AquaCrop model mainly simulates the response of crop biomass and yield to soil moisture. It determines the final yield as a function of the final biomass of the crop. In AquaCrop, the amount of water stored in the root zone is simulated by accounting for the incoming and outgoing water fluxes at its boundaries. Water balance in the root zone determines the magnitude of soil moisture affecting: green canopy expansion, canopy senescence and decline, root system deepening rate, stomatal conductance and hence transpiration, and the harvest index. Cold temperature stress resulting from prolonged excess moisture conditions reduces crop transpiration, inhibit pollination and reduce harvest index (HI).

In AquaCrop model, response of excess moisture on crop yield is simulated in following four steps. Excess moisture conditions directly affect one or more of the below processes.

1- Crop Development
2- Crop Transpiration
3- Biomass Production
4- Yield Formation

Crop Development:

When simulating crop development, AquaCrop uses green canopy cover to describe crop development. Through canopy cover expansion, it determines the amount of biomass produced and the final yield.

$$\text{Canopy Cover} = \frac{\text{Soil surface covered by the green canopy}}{\text{Unit ground surface area}}$$

Value for canopy cover ranges from 0 (bare soil) to 1 (full canopy cover). Excess moisture conditions in the crop root-zone might limit the canopy cover or crop development due to poor aeration, reduced root respiration, and changes in the soil redox potential.

Crop Transpiration:

Crop transpiration (Tr) is calculated by multiplying ETo with the crop transpiration coefficient (KcTr) and by considering the effect of water (Ks) and cold (Ks_{Tr}) stress.

$$Tr = (Ks * Ks_{Tr} * Kc_{Tr})\ ETo$$

The crop coefficient is proportional to canopy cover and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. Evapotranspiration is expressed by the reference grass ETo as determined by the FAO Penman-Monteith equation. Soil moisture extremes does not only affect canopy development but might also induce stomata closure and hence affect, also directly, crop transpiration.

Biomass Production:

The above ground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity.

$$B = WP * \Sigma\ Tr$$

Where,

B = Final biomass

WP = Water productivity (biomass per unit of cumulative transpiration)

Tr = Crop transpiration.

The WP parameter is based on the atmospheric evaporative demand and the atmospheric CO^2 concentration for the purpose of being applicable to diverse locations and simulating future climate scenarios. Following equation shows the procedure for calculating the normalized WP based on adjustments to annual CO^2 concentrations.

$$\mathrm{WP} = \left(\frac{B}{\Sigma\left(\frac{Tr}{ET_0}\right)} \right)_{CO_2}$$

Where,

CO_2 = Mean annual CO_2 concentration

ET_o = Atmospheric evaporative demand

The CO_2 outside the bracket is the normalization concentration for a given year.

Yield Formation:

The proportion of biomass that becomes harvestable yield is calculated using a harvest index parameter that increases over the growing season and responds to moisture extremes. Once the final biomass is calculated at harvest, the final yield output is the function of the final biomass (B) and the harvest index (HI).

$$Y = HI * B$$

Where,

Y = Dry Yield

B = Total dry above-ground biomass produced at crop maturity

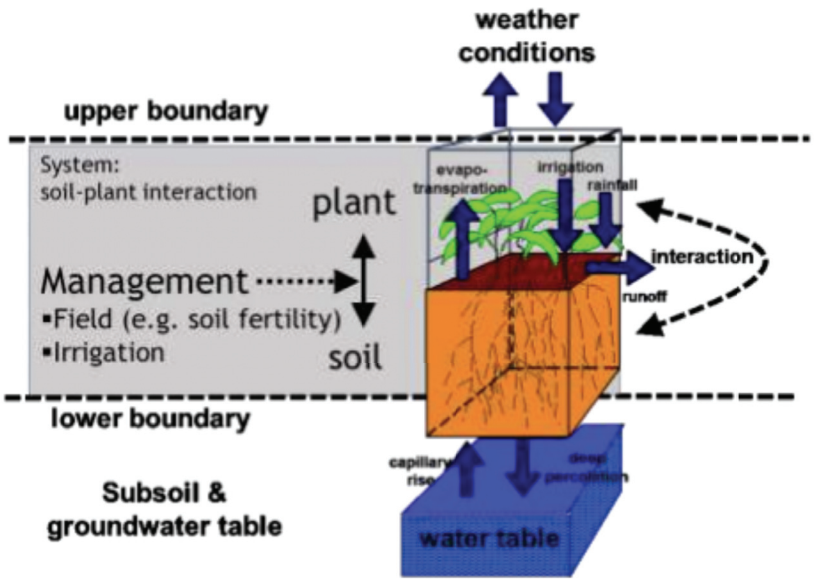
HI = Harvest Index (the fraction of B that is the yield part)

HI is the ratio between the harvested product and the total above ground biomass (Unkovich et al., 2010). In response to soil moisture extremes, HI is continuously adjusted during yield formation.

Model Input Data Requirements:

AquaCrop model system develops an interaction between plant and soil, which is effected by management, and link it with the outside world i.e. upper boundary (climate/weather conditions), and lower boundary (groundwater). A schematic function of AquaCrop working principal and model inputs are shown in Figure 3. The model uses separate input components of climate data, crop parameters, management (irrigation and field), soil (soil characteristics and groundwater) and simulation period for simulating crop yield.

Figure 3: AquaCrop Schematics (Raes, 2017)



The AquaCrop model includes five module to connect the soil-crop-atmosphere continuum.

1- Climate Module

2- Crop Module

3- Management Module

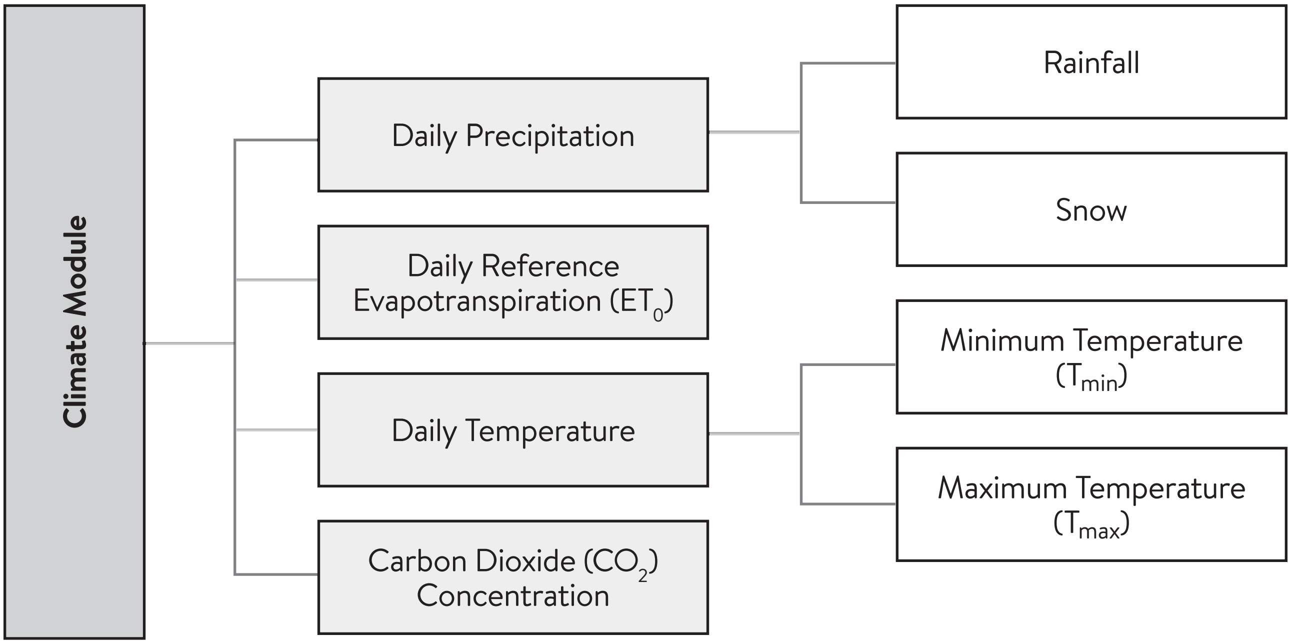
4- Soil Module

5- Simulation Module

Climate Module:

The climate module of the continuum is shown in Figure 4. It represents rainfall, reference evapotranspiration, air temperature, and atmospheric CO_2. For each day of the simulation period, AquaCrop requires precipitation, minimum (T_{MIN}) and maximum (T_{MAX}) air temperature, reference evapotranspiration (ET_o) as a measure of the evaporative demand of the atmosphere. Soil moisture and temperature extremes affect crop development (phenology), growth and biomass accumulation. Precipitation and ETo are determinants for the water balance of the root zone and air CO_2 concentration affects biomass water productivity.

Figure 4: Climate module of soil-crop-atmosphere continuum in AquaCrop model



Crop Module:

The crop module of the continuum is shown in Figure 5. It represents plant growth, development and yield processes. The database of AquaCrop requires crop files calibrated based on crop parameters for each crop. Crop parameters are categorized based on crop characteristics. AquaCrop requires following crop parameters in the calibration process:

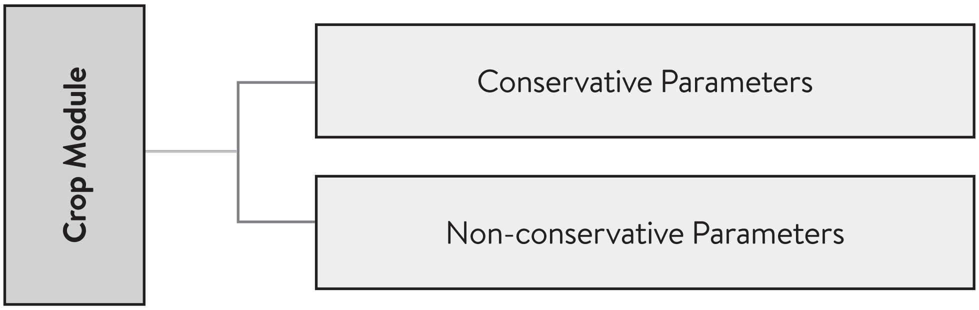
Conservative crop parameters:

These parameters do not change substantially with time, management practices, geographic location or climate. They are also assumed not to change with cultivars. Examples are the thresholds for extreme moisture levels and the normalized biomass water productivity. Conservative parameters do not require adjustment to the local conditions.

Non- conservative parameters:

Cultivar specific or non- conservative parameters are affected by planting, field management, conditions in the soil profile, or the weather. AquaCrop requires localized cultivar-specific parameters that describe the crop development stages in order to achieve reasonable crop simulations. Examples are the length of the growing cycle and plant density. While the crop cycle will always go through the same development stages, the timing of a crop cycle is dependent on the geographical location.

Figure 5: Crop module of soil-crop-atmosphere continuum in AquaCrop model



Management Module:

The management module of the continuum is shown in Figure 6. Management module allows calibrating the model in different soil moisture extremes, and soil moisture management strategies to assess the simultaneous impact of excess moisture levels as well as excess moisture management strategy on crop yield. This module is divided into two categories:

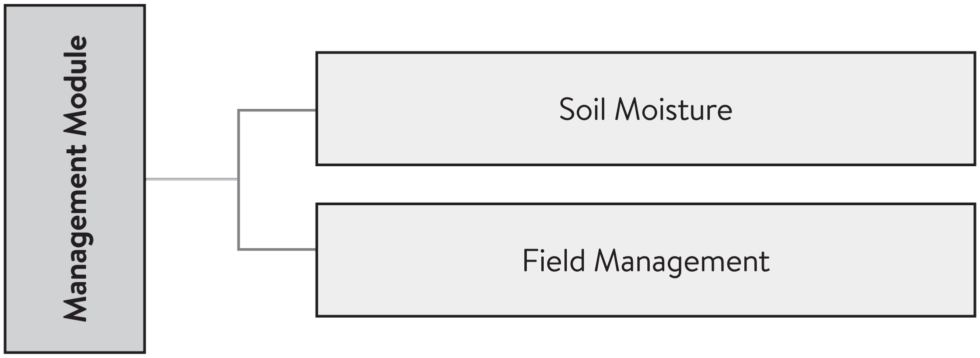
Soil moisture:

In this category, the user chooses whether the crop is rain-fed or irrigated. If irrigated, the user can select the application method, the fraction of surface wetted, and specify for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount. There are also options to assess the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria might change during the season, the program provides the means to test soil water balance in the root zone by applying chosen amounts of water at various stages of crop development.

Field management:

In this category, the user has choices of soil fertility levels, weed management, and practices that affect the soil water balance such as water retention pond (water reservoir) to store water on the field, land forming etc. as excess moisture management strategies. These management practices are described in detail in the Activty-1 of this project.

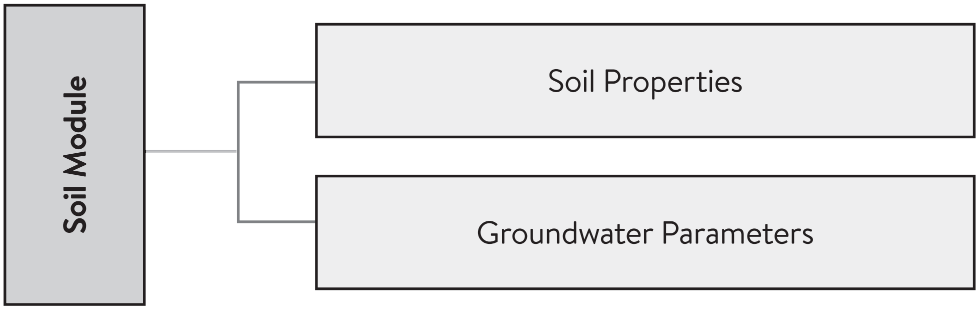
Figure 6: Management module of soil-crop-atmosphere continuum in AquaCrop model



Soil Module:

The soil module of the continuum is shown in Figure 7. The soil component of the module is focused on the water balance within the soil. The soil profile can be composed of up to five different horizons of variable depth, each with their own physical characteristics. The characteristics are the water retention in the fine soil fraction at saturation, field capacity, and at permanent wilting point, and the hydraulic conductivity of the soil at saturation (Ksat). In the groundwater component of the module, the user can choose between the presence and the absence of water table. The considered characteristics of the groundwater table are: groundwater depth below the soil surface, groundwater salinity.

Figure 7: Soil module of soil-crop-atmosphere continuum in AquaCrop model



Simulation Module:

The climate module of the continuum is shown in Figure 8. It requires simulation period, and initial field condition to simulate the crop area under study.

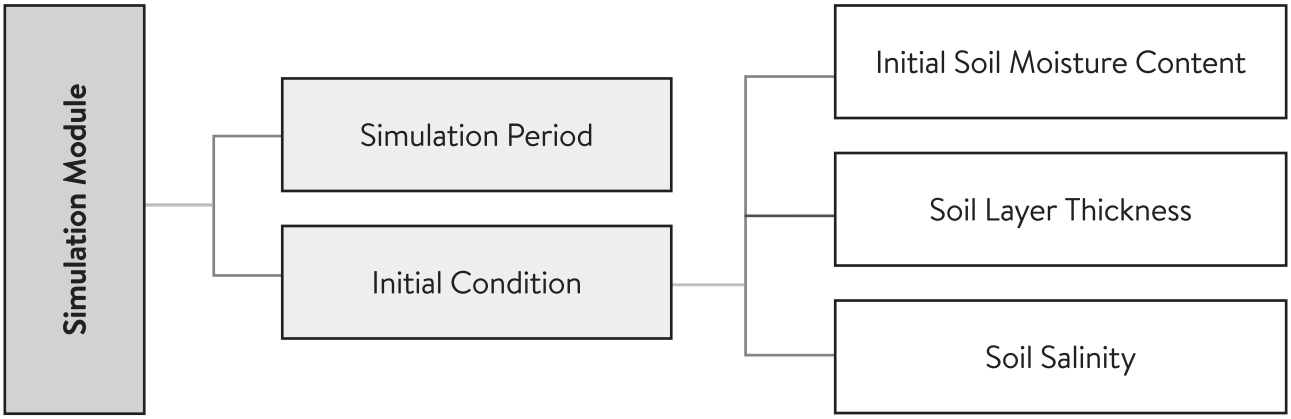
Simulation Period:

Simulation period refers to the growing cycle of the crop under study. The time period between the date of planting and date of harvesting the crop is referred as simulation period.

Initial Condition:

To start the simulation of the soil moisture content and salt balance of the root zone, the initial conditions need to be specified. Given the initial soil water and salt content, AquaCrop calculates the amount of water and salts retained in the root zone for the rest of the simulation period.

Figure 8. Simulation module of soil-crop-atmosphere continuum in AquaCrop model



Method

Version 6.1 of AquaCrop standard windows programme was downloaded from the website of Food and Agriculture Organization (FAO) to calibrate the model in Manitoba's Metrological conditions. This version of AquaCrop allows for language selection of the interface in English and French.

Model Calibration:

Model input data was collected using different local and global sources. Model calibration steps and data sources are summarized below:

Climate Module:

Agriculture and Agri-Food Canada (AAFC) has developed and thoroughly tested a Canada-wide interpolated spatial model of daily minimum and maximum temperature and precipitation (Hutchinson et al., 2009) with the added refinement of climate data using local weather stations (Hopkinson et al., 2011).The AAFC 1990-2019 dataset was used to create the precipitation and temperature input files (.PLU and .TMP). Daily mean weather data of Southern Manitoba with a focus on Assiniboine River, and Red River basins were used to calibrate the model in Manitoba's climatic conditions.

Reference Evapotranspiration (ET_o) values were calculated with the standardized Penman Monteith equation ($.ET_o$). Air temperature, mean of relative humidity, solar radiations, and wind Speed data at 10 m above ground was required to calculate daily reference evapotranspiration from the standardized Penman Monteith equation. AquaCrop provides default global atmospheric CO_2 values recorded from the Mauna Loa observations ($.CO_2$). Based on the four created parameter files, a climate file (.CLI) was created that will allow annual simulations of 30 years (1990-2019). Detailed sources of climatic data collected to calibrate the climatic module of soil-crop-atmosphere continuum of AquaCrop model in the Southern Manitoba's local conditions is enlisted in Table 2.

Table 2: Climatic data sources to calibrate the climatic module of AquaCrop

Data	Source
Minimum Temperature	Environment and Natural Resources Canada
Maximum Temperature	Environment and Natural Resources Canada
Precipitation (Rainfall and Snow)	Environment and Natural Resources Canada
Mean of Relative Humidity	POWER – A web based GIS application by NASA
Wind Speed at 10 m above ground	POWER – A web based GIS application by NASA
Solar Radiations	POWER – A web based GIS application by NASA
Reference Evapotranspiration	FAO Penman-Monteith equation
Global Atmospheric CO_2 Concentration	Mauna Loa Observatory in Hawaii

Crop Module:

Crop input parameters were derived from AquaCrop's default file (.CRO). The database of AquaCrop contains crop files in which the calibrated and fully validated crop parameters are stored. The shorter growing season of the Canadian prairies required updated crop values from the given default values. The file was modified to Manitoba's local conditions based on data collected from various local sources (Entz et al., 1992; Toure et al., 1995; Bennett and Harms, 2011, McKenzie et al., 2011; Mkhabela and Bullock, 2012). The other non-conservative parameters that describe the key stages of crop phenology, such as growing degree days (GDD) from seeding to emergence, start of flowering and maximum rooting depth, senescence, maturity and length of flowering, were added into the calibration algorithm.

When a crop is not available in the data bank, a crop file can be created by specifying only the type of crop (fruit or grain producing crops; root and tuber crops; leafy vegetables, or forage crops) and the length of its growth cycle. Based on this information AquaCrop provides defaults or sample values for all required parameters. In the absence of more specific information, these values can be used. Through the user interface, the defaults can be adjusted.

Management Module:

In the management module, AquaCrop allows the user to adjust soil water balance in the root zone. The user can adjust soil moisture levels within the soil profile to assess the impact of soil moisture extremes on crop yield. The user also has the choice of selecting or manually inserting local soil fertility levels, weed management, and practices that affect the soil water balance such as water retention pond (water reservoir) to store water on the field, land forming etc. as excess moisture management interventions. This module supports producers in making on-farm investment decisions related to managing times of excess moisture to reduce the potential disaster as a result of a flood event. These management practices are described in detail in the Activty-1 of this project.

Soil Module:

The user can make use of the indicative values provided by AquaCrop for various soil texture classes, or import locally determined or derived data from soil texture. A common method for expressing physical properties of soils is based on the USDA soil triangle. The USDA soil triangle derives percentages of sand, silt, and clay content for classifying hydraulic parameters (Cosby et al., 1984). Different types will have differences in their responses to soil moisture extremes. Field capacity, permanent wilting point, and soil moisture at saturation are important soil characteristics that depend on soil textures and enable the quantification of plant available water for the assessment of soil response to excess moisture.

AquaCrop allows for the input of up to five different soil horizons into the .SOL file. Each horizon requires the following soil data: soil water content at saturation (Sat), field capacity (FC), permanent wilting point (PWP), and depth. For model simulation purpose, these values may be obtained from USDA's Soil Water Characteristics program. Soil Water Characteristics is a program that is used to simulate soil water tension, conductivity and water-holding capability based on the soil texture, with adjustments to account for gravel content, compaction, salinity, and organic matter. Soil Water Characteristics program can be downloaded for free from the USDA website (https://www.ars.usda.gov/research/software/download/?softwareid=492&modecode=80-42-05-10#downloadForm).

Another important component of soil module is groundwater properties. Depth of the water table and quality is entered in the AquaCrop model for the field under study.

Simulation Module:

In this module, the user can launch the simulation to run model for a given simulation period. The simulation will advance to the end of the simulation period. In case of multiple runs projects, the simulation advances to the end of the simulation period of the specified run number by the specified number of days or to a specified date. The start of the simulation period should coincide with the crop planting date. Once the plant reaches maturity the Harvest Index (HI) will stop increasing (Steduto et al., 2009), hence simulated yield will not increase after maturity. The initial soil moisture content and salt content can be obtained by measuring the soil moisture and salt content in the soil profile. For this purpose, soil sampling is done at the day of planting.

Conclusion

The goals of this report is to contribute to informing farmers, agricultural industry, farm production consultants, planners, and economists in Manitoba in making fact-based business decisions at the nexus of crop yields and excess moisture conditions, based on the AquaCrop model. A model calculates impacts of climate change and CO_2 fertilization on crop yields. In order to help further our understanding, Rural Development Institute of Brandon University simulated a farm model with 30 years of data on Manitoba's regional conditions for estimating future excess moisture impacts. After careful review of multiple models, the best suited crop water productivity model called AquaCrop was selected. Developed by the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO), it has a user-friendly interface and does not require extensive modeling knowledge. Communicating with visually proms, this model simplifies the complexity by showing the user how the various components interact. With the results, producers make informed choice based on probability calculated using long-term climatic data. For example, precise yield predictions before seeding help producers to maximize their income through crop management options and financial decisions (e.g., plant alternative crops and buy crop insurance); these would be based on climatic conditions before the start of the growing season and/or seasonal climatic forecasts for the upcoming growing season. As a result, the success of a farm model contributes to enhancing the producers' foundation of biophysical processes linked to crop yields with sound predictors of local conditions.

Future prospects for the agriculture industry will continue to seek a better understanding of impacts of climate change on agriculture production. The AquaCrop model with its focus on crop yield forecasts based on long term metrological variations on crop yield, allows managing risk associated with moisture extremes (excess or deficit), and aids in appropriate mitigation decision making. Regional yield forecasting can assist marketing agencies, and commodity brokers, in their planning to maximize sales opportunities. Taking a broader view, the results from the AquaCrop model seem to offer important prospects of informing evidence-based decisions about food security while incorporating climate-based yield forecasts, throughout a growing season.

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